COATING PROCESSES

1. Introduction

Coating process technology is in widespread use because there are few single materials that are suitable for the intended final use without treating the surface (1–7) to meet all the functional needs and requirements of the product. The modification is accomplished by applying a coating or series of coatings to the material—the substrate—to improve its performance and make it more suitable for use, or to give it different characteristics. The coating process is defined here as replacing the air at a substrate with a new material—the coating.

Typical coatings are the paints and the diverse surface coatings used to protect houses, bridges, appliances, automobiles, etc. These coatings protect the surface from corrosion and degradation, and may provide other functional advantages such as making the materials waterproof or flameproof, and improving the appearance. Adhesives are applied to paper or plastic to produce labels and tapes for a variety of uses. A thin layer of adhesive is coated onto paper to produce self-sticking note pads. Glass windows are coated with a variety of materials to make them stronger and to control light penetration into the structure. High energy lithium batteries contain coated structures. Plastic food wrap has layers to reduce oxygen penetration and retain moisture for the product to retain its freshness. Packaging materials for electronic products are coated with antistatic compounds to protect the sensitive components. Other important coated products are photographic films for medical, industrial, graphic arts, and consumer use; optical and magnetic media for audio and visual use data storage; printing plates; and glossy paper for magazines.

Several industries are based on coating process technology. Printing itself is a coating process, and much of the paper used in the printing industry had previously been coated to improve its gloss, strength, and ink acceptability. Lithographic printing plates for printing presses are photosensitive coatings on aluminum. Photographic film, itself a coated product, is used to expose the plates, set the type, and prepare the printed pictures. The entertainment industry uses magnetic tape, silver halide film, and coated optical disks to record the material for distribution to the consumer. The electronics industry uses coated products such as photoresist films to fabricate circuit boards and to add functionality to the circuit boards. The computer industry stores information on coated magnetic structures such as hard drives and floppy disks.

2. Coating Machines

The basic steps in continuously producing a coated structure are

1. preparing the coating solution or dispersion
2. unwinding the roll of substrate
3. transporting it through the coater
4. applying the coating from a solvent, or as a liquid to be cross-linked, or from the vapor
5. drying or solidifying the coating
6. winding the final coated roll
7. converting the product to the final size and shape needed

Other operations that are often used are

1. surface treatment of the substrate to improve adhesion
2. cleaning of the substrate prior to coating, to reduce contamination
3. lamination, where a protective cover sheet is added to the coating structure.

Different types of machinery are used to produce coated products. Depending on the substrate, they can be web coaters, sheet coaters, and coaters for non-flat applications. Web coaters, the most prevalent, coat onto continuous webs of material. Magnetic tapes, window films, wallpaper; barrier coatings for plastic films, and many printed goods are all produced using this process. A typical web coater with all the process steps is shown in Figure 1.

These machines are commercially available in sizes from pilot coaters using narrow webs, 6–24 in. wide, and running at low speeds, 10–50 ft/min, to production machines using wide webs, over 5 ft wide and coating at 500–5000 ft/min. A typical pilot coater is shown in Figure 2.

Sheet coaters are available to coat individual sheets. Many printing operations and all copying machines are sheet-fed. Sheet coaters are also used as laboratory coaters to develop new products where many different solutions need to be coated and only small volumes of sample are available. These methods use a variety of devices such as draw-down blades, dies, or wire-wound rods to spread a uniform layer of solution across the web. Most applicators can provide

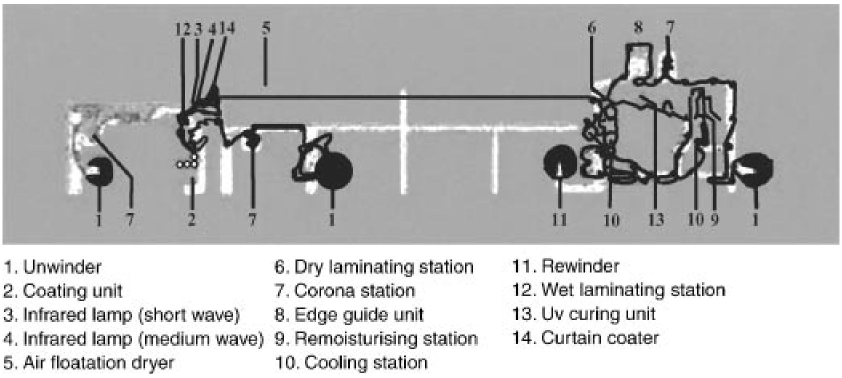

Fig. 1. Coating line showing components. Courtesy of Polytype America Corp.

wet coverages of 0.2–50 mil (5–1270 μm). Spray coaters may also be used to coat sheets. The coated webs or sheets are then dried by ambient air or in an oven. Laboratory automated sheet coaters are available. These give better reproducibility and control but are more expensive than hand applicators. They can be coupled to feed directly into dryers, with the temperature and residence time controlled, as shown in Figure 3.

In nonweb applications the coating is applied to a specific part at the end of the fabrication process. The part is usually three-dimensional and of varying shape. Automobiles, appliances, and steel structures all have the coating applied to the individual items as they are being built. It should be noted that many smaller steel items are made from prepainted sheet steel.

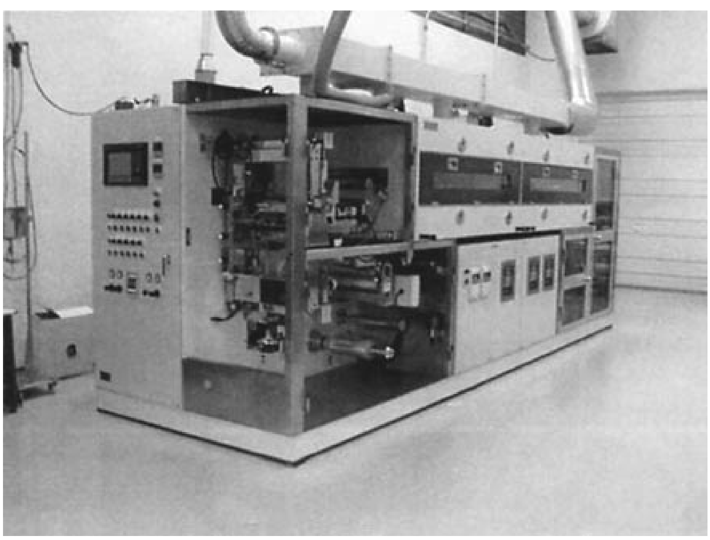

Fig. 2. Pilot coater. Courtesy of Texmax, Inc.

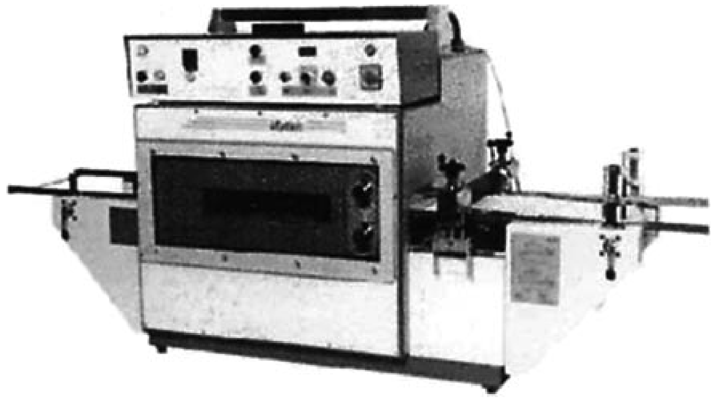

Fig. 3. Laboratory bench-top coater. Courtesy of Werner Mathis.

3. Coating Processes

The application of a liquid to a traveling web or substrate is accomplished by one of the many coating methods. Widely used commercial coating methods are reverse roll, wire-wound or Mayer rod, direct and offset gravure, slot die, blade, hot melt, curtain, knife over roll, extrusion, air knife, spray, rotary screen, multilayer slide, coextrusion, meniscus, comma and microgravure coaters (based on analysis of methods reported by coaters in various trade sources). Each of these has many designs and hardware arrangements leading to many specific coating configurations. Powder coating is covered in the article Coating Methods, Powder Technology.

The choice of the method depends on the nature of the support to be coated, the rheology of the coating fluid, the solvent, the wet-coating weight or coverage desired, the needed coating uniformity, the desired coating width and speed; the number of layers to be coated simultaneously, cost considerations, environmental considerations, and whether the coating is to be continuous or intermittent.

The method should be chosen based on the specific requirements. Often a method is selected based on the availability of a specific coating applicator, even though it may not be the best choice. All applicators can apply a coating at some conditions. Much time and money can be wasted by trying to make the product by a process that is not suitable. The coating window may be too narrow at the conditions selected, or it may be impossible to ever obtain a quality coating. The successful process will provide defect-free film over a wide range of conditions. A process that works well at low speeds in the laboratory may not be appropriate for a manufacturing plant coating at high speeds, and conversely, a high speed coating process may not be appropriate for laboratory trials.

The first step in the selection process is to establish the requirements for the product to be coated. These requirements are then matched with the capabilities of the process and the best methods are evaluated experimentally to determine the one to use. Some of the basic characteristics of the principal coating processes are listed in Table 1.

Table 1. **Summary of Coating Methods**[a]

Process	Viscosity, mPa · s (= cP)	No. of layers	Wet thickness, μm	Coating accuracy, %	Max. speed, m/min
Self-metered					
Rod	20–1000	1	5–50	10	250
Dip	20–1000	1	5–100	10	150
Forward roll	20–1000	1	10–200	8	150
Reverse roll	100–50,000	1	5–400	5	400
Air knife	5–500	1	2–40	5	500
Knife over roll	100–50,000	1	25–750	10	150
Blade	500–40,000	1	25–750	7	1500
Premetered					
Slot	5–20,000	1–3	15–250	2	500
Extrusion	50,000–5,000,000	1–3	15–750	5	700
Slide	5–500	1–18	15–250	2	300
Curtain	5–500	1–18	2–500	2	300
Hybrid					
Gravure, direct	1–5000	1	1–25	2	700
Gravure, offset	100–50,000	1	5–400	5	300
Microgravure	1–4000	1	1–40	2	100

[a] Values given are only guidelines.

The processes are grouped according to the principle used to control the coverage or coating weight of the coating and its resulting uniformity. We have three groupings, but there are no generally accepted definitions of the terminology we use: self-metered, premetered and hybrid. Self-metered processes are those in which the coverage is a function of the liquid properties and the system geometry, the web speed, the roll speeds, and any doctoring device. Examples are dip coating in which viscosity and web-speed control coverage, and blade and air knife coating in which excess is applied and then removed. Premetered processes deliver a set flow rate of solution per unit width to the applicator and all the material is transferred to the web. If a smooth coating is obtained then the coverage is fixed. Hybrid processes use features of both self- and premetered coating to achieve coating weight control. Gravure is an example of this method. The cell transfer determines coverage but doctoring is used to remove excess fluid from the gravure cylinder.

In most coating operations a single layer is coated. When more than one layer must be applied one can make multiple passes, or use tandem coaters where the next layer is applied at another coating station immediately following the dryer section for the previous layer, or a multilayer coating station can be used. Slot, extrusion, slide, and curtain coaters are used to apply multiple layers simultaneously. Slide and curtain coaters can apply an unlimited number of layers simultaneously, whereas slot coaters are limited by the complexity of the die internals and extrusion coaters by the ability of the combining adapter, ahead of the extrusion die, to handle many layers.

The precision or uniformity of the coating is very important for some products such as photographic or magnetic coatings. Some processes are better suited for precise control of coverage. When properly designed, slot, slide, curtain, gravure, and reverse-roll coaters are able to maintain coverage uniformity to within 2%. In many of the other coating processes the coverage control may be only 10%. Table 1 lists generally accepted attainable control.

The substrates or support coated on include paper and paper board, cellophane, poly(ethylene terephthalate), poly(ethylene naphthalate), polyethylene, polypropylene, polystyrene, poly(vinyl chloride), poly(vinyl fluoride), poly(vinylidene fluoride), polyimide, metal foils, woven and nonwoven fabrics, fibers, and metal coils. The surfaces of these supports can be impervious as in plastic films, or there may be a pore structure such as in paper. Primer coatings may be applied to seal these pores to give a uniform surface for the coating and to improve adhesion. The surfaces can also be modified with surface treatments such as flame treatment, plasma treatment, or corona discharge. These treatments increase the surface energy, thereby improving wetability and adhesion.

The web coating process can be used for intermittent coatings, such as in the printing process and to form coated batteries, as well as for the more common continuous coatings such as photographic films. In general, there is an ideal coater arrangement for any given product. However, most coating machines produce many different products and coating thickness and the machine is therefore usually a compromise made for the several applications.

3.1. Limits of Coatability. In any coating process there is a maximum coating speed above which coating does not occur. At higher speeds air is entrained, resulting in many bubbles in the coating, or in ribs and finally rivulets, or in wet and dry patches. In slot coating below a critical speed, to coat thinner often means to coat slower. Above the critical speed the minimum thickness depends only on the gap. Above some higher speed a coating cannot be made (5). Using bead vacuum, thinner coatings can be obtained. Similar effects were found in slide coating, except the critical speed is never reached (6). The maximum coating speed in slide coating for thick coatings, where no bead vacuum or electrostatic assist is used, is identical to the velocity of air entrainment for a tape plunging into a pool of coating fluid. Lower viscosity liquids can be coated faster and thinner. Polymer solutions can be coated at higher speeds than Newtonian liquids. These phenomena have been explained in terms of a balance of forces acting on the coating bead, ie, the coating liquid in the region where it first makes contact with the web (7). Stabilizing forces are mainly bead vacuum or electrostatic assist, if used. The destabilizing forces are primarily the drag force on the coating liquid and the momentum of the air film carried along by the web. Thus, with no bead vacuum or electrostatic assist, there is a net destabilizing force which is balanced by the cohesive strength of the liquid. Limits of coatability occur in all coating operations but under different conditions in each process. A good description of the window of coatability in slot coating can be found in Reference 8.

The air entrainment velocity for plunging tapes does not depend on the wettability of the surface, but does increase with surface roughness (9,10). Presumably the rough surface lets air that would otherwise be entrained escape in the valleys between the peaks that are covered with coating liquid (11). In the converting industry, which involves coatings on rough and porous paper surfaces, much higher (up to 25 m/s) coating speeds can be attained than in photographic coatings on smooth plastic films. Although the wettability itself plays little or no role in coatability, it does play an extremely important role in coating. On a nonwetting surface, immediately after coating, the fluid will dewet and ball up into distinct islands.

3.2. Knife and Blade Coatings. Knife and blade coatings are in many ways similar. In both cases the knife or the blade doctors off excess coating that has been put on the web. Knives are usually held perpendicular to the web, whereas blades are usually tilted so that they form an acute angle with the incoming web. Typically blades are thin, only 0.2–0.5 mm thick, and can be rigid or flexible (of spring steel). Knives are thicker and are always rigid. Blades, being thinner, wear faster and have to be changed relatively often, perhaps two to four times a day. Blades are always pressed against the web, which is supported by a backing roll either made of chrome-plated steel or rubber-covered. Knives may be pressed against web on a rubber-covered backing roll; they may be pressed against the unsupported web which is held taut by the tension in the web; or they may be held at a fixed gap from the web that is supported by a backing roll.

The ends of the knives can be square, beveled or rounded. If the end is square and parallel to the web, if the upstream face is perpendicular to the web, and if there is a fixed gap between the end of the knife and the web, then the wet coverage is exactly one-half the gap. On the other hand, if there is a low angle in a converging section of the knife or of the blade, leading up to a tight gap as there is for many knives and for all bent blades, then strong hydrodynamic forces build up and tend to lift the knife or blade away from the web. This forces more fluid under the knife or blade, so that the coated thickness is greater than half the gap.

In all cases of knife and blade coatings, except in knife coating at a fixed gap, a rigid member and a flexible member are pressed together. The flexible member can deflect to allow for nonuniformities in the web. In knife coating and beveled blade coating, the knife or blade is rigid, and the unsupported web or the web on a rubber-covered roll is flexible. In bent blade coating the blade is flexible and the web on the roll is rigid or relatively rigid as in the case of a rubber-covered roll. Knife coating against unsupported web is more difficult to control than the other knife- and blade-coating techniques because, here, the web tension is a very important variable.

The simplest and least expensive, but still effective, coating method is knife coating, either against a backing roll or on unsupported web. Coating against a backing roll is more accurate, as it is independent of web tension. The knife, held perpendicular to the web, acts as a doctor blade and removes excess coating liquid. The coating can be applied by any convenient method, such as with an applicator roll, or by pumping the fluid into a pool formed by the web, the knife, and two end dams. The control of the coverage is by proper positioning of the knife. The unsupported knife shown in Figure 4**a** is used for coating open fabric webs where coating penetration is desired or cannot be prevented. A full width endless belt can be used to support a weak web and pull it through the knife area without tearing so as to overcome the drag of the knife.

The knife over roll coater (Fig. 4**b**) is probably the most common of the knife coaters. It is simple and compact. The driven back-up roll may be precision-made and chrome-plated, having a controlled gap between the web

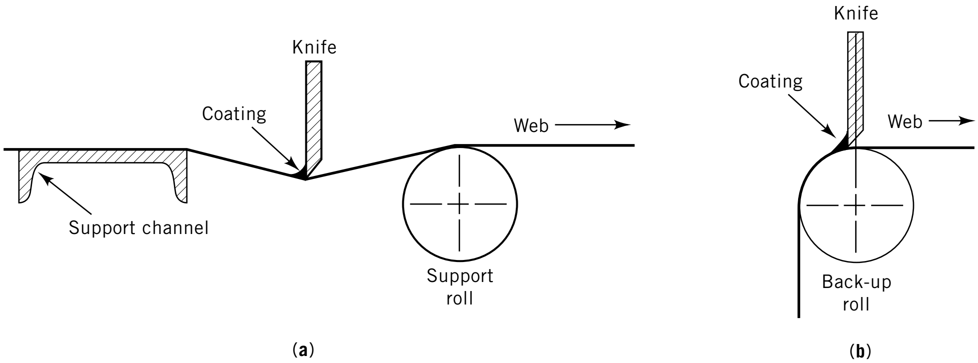

Fig. 4. (**a**) Unsupported knife; (**b**) knife over roll.

and the knife. The backing roll may also be rubber-covered, the knife pressing against the web. Here the coating weight is determined by the pressure against the knife. Higher pressures give lower coating weights.

Knife coaters can apply high coverages, up to 2.5-mm wet, and can handle high viscosities, up to 100,000 mPa · s(= cP). They tend to level rough surfaces rather than give a uniform coverage, a characteristic that can be desirable or not depending on the needs of the finished coating. Streaks and scratches are hard to avoid, especially using high viscosity liquids.

Blade Coating. Flexible blade coaters can be used either with a downward moving web, as shown in Figure 5**a**, or with an upward moving web, as shown in Figure 5**b**. As with knife coaters there are many ways of feeding the metering blade. A puddle behind the blade is shown in Figure 5**a**, a forward turning applicator roll in Figure 5**b**, and a slot applicator or die fountain in Figure 5**c**. Jet fountains, where the coating liquid spurts out to the web 25–50 mm away, are occasionally used.

Blade coaters are commonly used on pigmented coatings. They have the unique feature of troweling in the low areas in a paper web, thus producing a coated surface that has excellent smoothness and printing qualities. The backing roll is usually covered with resilient material and is driven at the same speed as the web to stabilize the web and draw it past the blade. A replaceable blade is rigidly clamped at one end and the unsupported end is forced against the substrate. The wet coverage is adjusted by varying blade thickness, the blade angle, and the force pushing the blade against the substrate. The force on the blade can be obtained by various means: a rubber tube between the blade and a rigid member can be inflated with varying air pressures or the blade holder can be rotated so as to apply a greater or lesser force at the tip, while keeping constant the angle the blade tip makes with the web.

As the force on the blade increases, and as the force is concentrated at the blade tip, the wet coverage decreases rapidly. However, further increases in force bend the blade and a larger area of the blade presses the liquid against the web. Increasing the loading of the blade then causes the tip to lift up and the coverage now increases. At further increases in load the coverage again decreases.

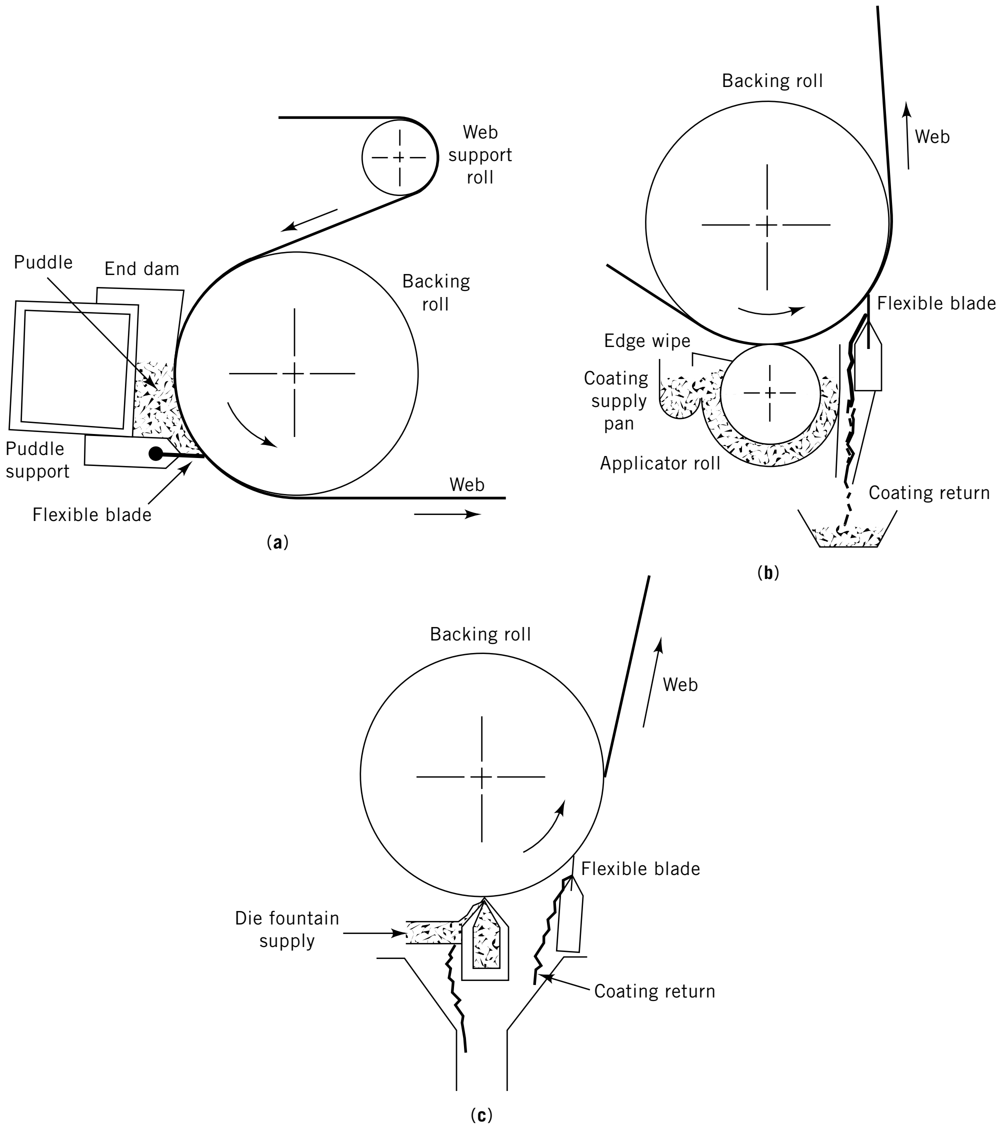

Fig. 5. (**a**) Puddle coater; (**b**) roll applicator blade coater; (**c**) fountain blade coater.

The beveled blade coater uses a rigid blade held at an angle of 40–55° to the web. The end of the blade is parallel to the substrate and pressed against it. If initially the end of the blade is not parallel to the web, it soon is as a result of abrasion by the pigmented fluid. When the loading on the blade increases, the wet coverage decreases. With the same force but using a thicker blade, the pressure, or force per unit area, on the coating fluid between the blade and the web decreases and the coverage increases.

In the rod–blade coater unit, a rod is mounted at the end of the blade. This coater behaves more like the beveled blade coater than a flexible blade coater.

Two-Blade Coaters. In order to coat both sides of a web simultaneously, two flexible blade coaters can be used back-to-back, ie, with both blades pressing against each other and the web between them. The web usually travels vertically upward. Different coatings can be applied on each side of the web. The blades tend to be thinner and more flexible than the standard blades and the angle to the web is lower. The web has to have sufficient tensile strength to be pulled through the nip.

Simultaneous coatings can also be made with one flexible blade against the web on the roll, where the web moves downward. On one side the coating fluid is supplied to a puddle in front of the blade, and on the other side the fluid is carried into the nip by the roll. Edge dams between the web and the blade and between the web and the roll keep the fluid contained. The roll may rotate faster than the web. Figure 6 shows a version where the fluid on the roll side is supplied by a transfer roll.

Air-Knife Coater. The air-knife coater is a versatile coating process in use for a wide range of products. A coating pan and roll are used to apply the coating solution and then an air knife is positioned after the pan to regulate the final wet-coating weight by applying a focused jet of air to the web. The excess solution is collected in an overflow pan and can be either recirculated and used again or scrapped. The air knife can function either in the precision or in the squeegee mode. These give very different types of coating and performance characteristics, although the same name is used for both processes.

In the precision mode, the air knife uses low pressures and doctors off some of the coating to control the coating weight and to level the surface to give a uniform coating of reasonable quality. The coating weight is a function of web speed, viscosity of solution, surface tension, and air-knife pressure. This precision mode has been used to coat photographic films where the air velocities are 13–130 m/min and air pressures are 50–2500 Pa (0.2–10 in. of water) to give 1- to 200-μm wet thickness.

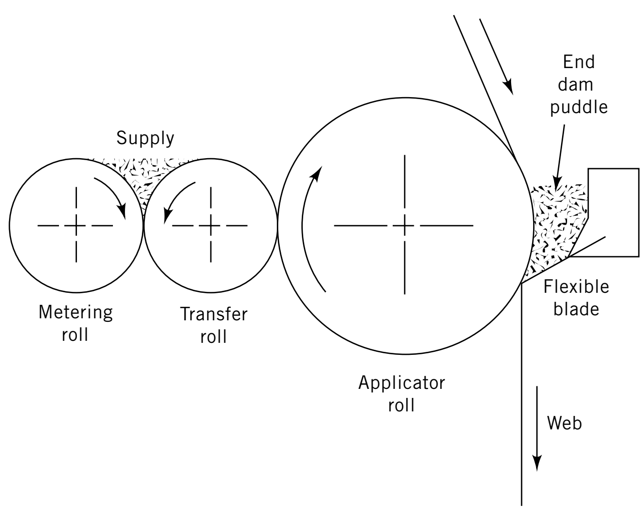

Fig. 6. Billblade with transfer rolls.

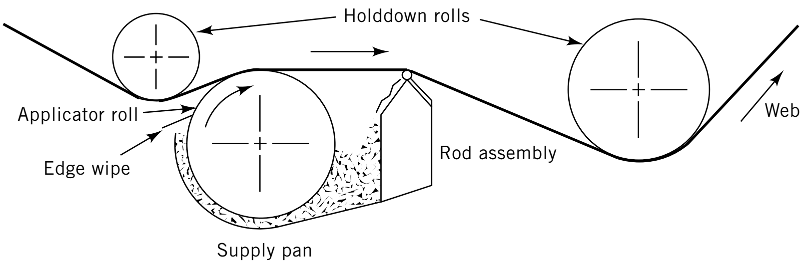

Fig. 7. Wire-wound rod coater.

In the squeegee mode, the air knife operates at much higher pressures and coating speeds than in the precision mode and effectively doctors off the majority of the coating. This process is used for porous supports, such as paper, where the coating is absorbed into the voids. After the air knife, which effectively functions as a leveling device, the coating solids remain in the voids and in a thin surface layer.

The advantages of the air-knife process are low initial cost, versatility for coating a variety of webs and solutions, ease of changing and maintaining the coating, and the good coating quality. The disadvantages are the noise and contamination problems created by the air stream and the resulting spray, solution viscosity limitations, a somewhat restricted coating weight range, and the high cost to operate the air blowers.

3.3. Wire-Wound Rod Coating. The wire-wound rod coater shown in Figure 7, called a Mayer rod, meters off excess applied coating solution. The rod is often rotated to increase its life by causing even wear and to prevent particles from getting caught under the rod and causing streaks. Normal rotation is in the reverse direction to the web travel. The wire size controls the coating weight. As the rod has an undulating surface because of the wire, one would expect the coating to have a similar unevenness. However, the down-web lines that form are frequently spaced at other than the wire diameter and are due to ribbing. If the solution is not self-leveling, a smoothing rod may be used to smooth out the surface. Rod coaters are best used with low viscosity liquids.

From the geometry of the wire-wound rod, one would expect the wet thickness to be 10.7% of the wire diameter. It is frequently less. It has been shown that with increasing load on the rod the wet thickness decreases to about 7% of the wire diameter (11).

Rod coaters are commonly used for low solids, low viscosity coatings such as those used to coat adhesives and barrier layers on poly(vinylidene chloride) carbon paper and silicone release papers. Coating weights range from 1.5–10 g/m^2, and speeds are as high as 300 m/min. The wire-wound rod can be held against unsupported web, as shown in Figure 6, or against a backing roll. When used against unsupported web the web tension affects the coverage. Coating rods are compact, simple, and inexpensive, but wear rapidly when used with abrasive fluids.

3.4. Roll Coating. *Meniscus or Bead-Roll Coater.* One of the simplest and most widely used coaters is the meniscus or bead-roll coater (Fig. 8). In this process the web passes over a backup roll that is just above the liquid level in a pan. A meniscus or coating bead is formed between the web and the

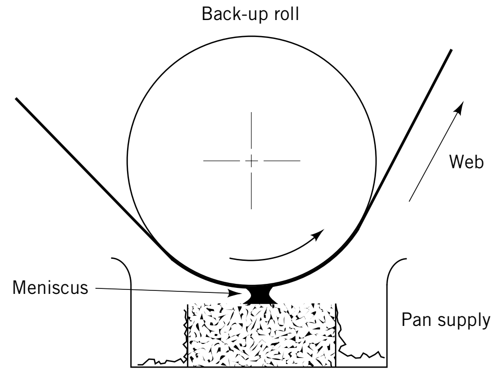

Fig. 8. Pan-type Meniscus coater.

coating solution by raising the pan, and the solution transfers to the web. The coverage is determined by the viscosity of the solution and the coating speed. The pan design is very critical and a variety of configurations are available. The coating speed is very slow, only about 10 m/min on low viscosity liquids. High quality optical coatings may be produced. These coaters have also been used for adhesives.

Kiss Coaters. In kiss coating fluid is transferred from a rotating applicator roll, called a kiss roll, to unsupported web. There are many types of kiss coaters. The kiss roll can turn in the direction of the web or in the reverse direction, but usually operates in the web direction. Kiss coaters are tension sensitive and are often used to apply excess coating prior to a metering device.

Forward-Roll Coaters. In forward-roll coating the web passes between two rolls rotating in the same direction, the applicator roll and the backing roll. The applicator roll drags fluid into the nip, as shown in Figure 9 (12). The fluid exiting the nip splits in two, with some adhering to the web and some to the applicator roll. One might expect that if both rolls are rotating at the same surface speeds, then the fluid between them should move at that same speed and the flow rate per unit width through the nip, q, would equal the product of the surface speed, U, and the gap in the nip, G. Actually it is more than this because of the buildup of pressure as the fluid approaches the nip, which produces a greater flow. The dimensionless flow rate γ is defined as the ratio of the actual flow rate per unit width to GU, the "expected" value, or

$$\gamma = \frac{q}{GU}$$

where U is now the average surface speed of the two rolls. The dimensionless flow rate is approximately equal to 1.3 to 0.5, depending upon conditions.

Each roll carries away some of the flow. The ratio of film thickness on the two rolls, t_2/t_1, depends on the speed ratio, and for Newtonian fluids is

$$t_2/t_1 = (U_2/U_1)^{0.65}$$

where the subscript 1 corresponds to the web and the subscript 2 to the applicator roll. The total flow through the gap per unit width, q, is equal to the sum of

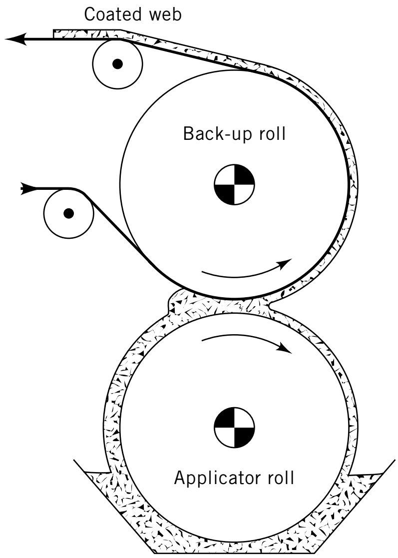

Fig. 9. Two-roll forward-roll coater (12).

the flow on the web, t_1U_1, and that on the exit side of the applicator roll, t_2U_2. With shear-thinning fluids, when the roll speeds differ the split is more symmetrical than the equation indicates.

In forward-roll coating it is fairly common to have an instability called *ribbing*, where the coating thickness varies sinusoidally across the web and the coating looks as if a giant comb were dragged down the wet coating. Ribbing occurs when the *capillary number*, *Ca*, the ratio of viscous to surface forces, exceeds a certain value, depending on the gap-to-diameter ratio. The capillary number is

$$Ca = \eta U/\sigma$$

where U is the average surface speed of the two rolls, η is the viscosity of the coating fluid, and σ is the surface tension.

It is very difficult to avoid ribbing in forward-roll coating. When the fluid is not self-leveling, a smoothing bar is often used to smooth out the ribs. It has been found that a fine wire or thread stretched across the gap exit and touching the liquid eliminates ribbing (10).

Reverse-Roll Coating. Reverse-roll coating is an extremely versatile coating method and can give a very uniform, defect-free coating (12–1200 μm thick) at a very wide range of coating speeds, using coating fluids with viscosities ranging from low to extremely high. In reverse-roll coating, the coating fluid is applied to the applicator roll by any of a number of techniques, such as having the applicator roll rotate in a pan of fluid, using a fountain roll or a fountain or slot die. The excess fluid is then metered off by a reverse-turning metering roll and the remaining fluid is completely transferred to the web traveling in the reverse direction. Two of the many possible configurations are shown in Figure 10.

All the flow remaining on the applicator roll after it rotates past the metering roll is transferred to the web; therefore it is important to know what this flow

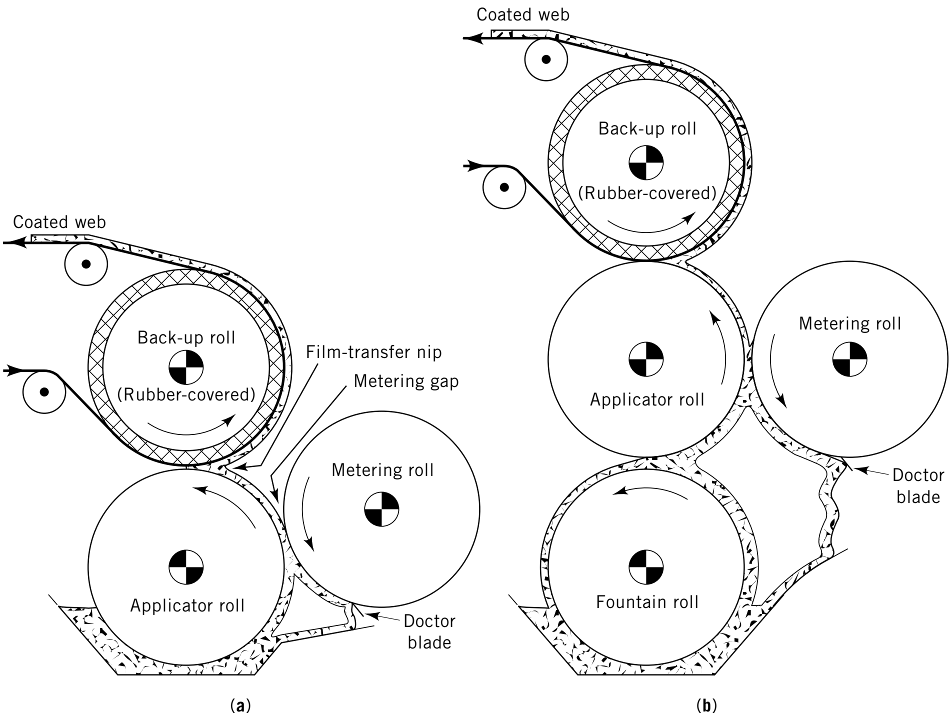

Fig. 10. Pan-fed reverse-roll coaters: (**a**) three roll; (**b**) four roll (12).

is. The thickness of the metered coating on the applicator roll, t_a, is found to be a function of the gap, of the ratio of the speed of the metering roll to that of the applicator roll, and of the capillary number based on the applicator roll speed (Fig. 11).

In reverse-roll coating, as in forward-roll coating, instabilities can form. However, it is possible to obtain defect-free coatings at high coating speeds. Sometimes increasing the speed can lead to a smooth coating when a ribbing condition is present.

Another defect, called cascade or seashore, can form in reverse-roll coating. This defect is caused by the entrapment of air under certain conditions and can appear in the metered flow on the applicator roll. An operability diagram, showing the region of stable flow as well as the regions where these defects form, is given in Figure 12 for two gaps. The region where stable coatings can be made is at high capillary numbers, ie, at high speeds. There is also a stable region at very low speeds, but low speeds are not usually desirable. The principal advantage of reverse-roll coating is that conditions can be adjusted to give a stable, defect-free coating at high coating speeds. Using precision bearings, reverse-roll coaters can lay down as uniform a coating as any coating process, about ±2%.

3.5. Gravure Coating. Gravure coating is an accurate way of coating thin (1- to 25-μm wet coverage) layers of low [10−5000 mPa · s (=cP)] viscosity liquids. The coating liquid is picked up by a patterned chrome-plated roll, the excess doctored off and the liquid transferred from the filled cells to the web.

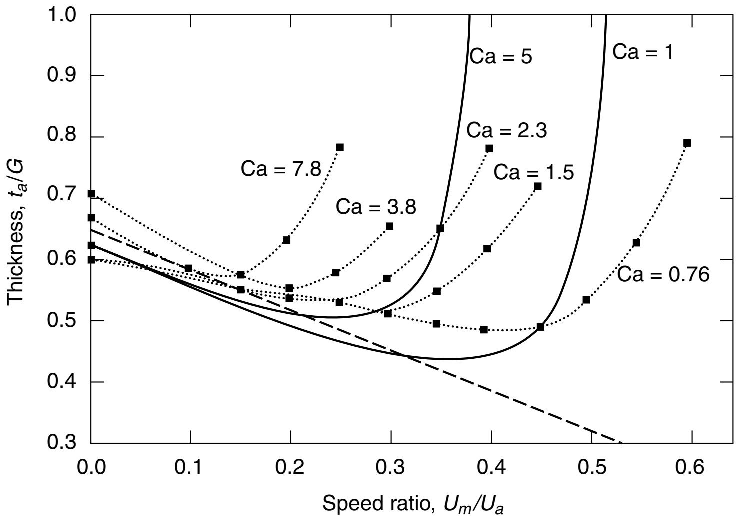

Fig. 11. Reverse-roll, metered film thickness on the applicator roll divided by gap, t_a/G, as a function of the ratio of the metering roll speed U_m to applicator roll speed U_a for various capillary numbers based on U_a. (—) represents theoretical values; (· · ·) experimental ones; and (– – –) is the lubrication model (12).

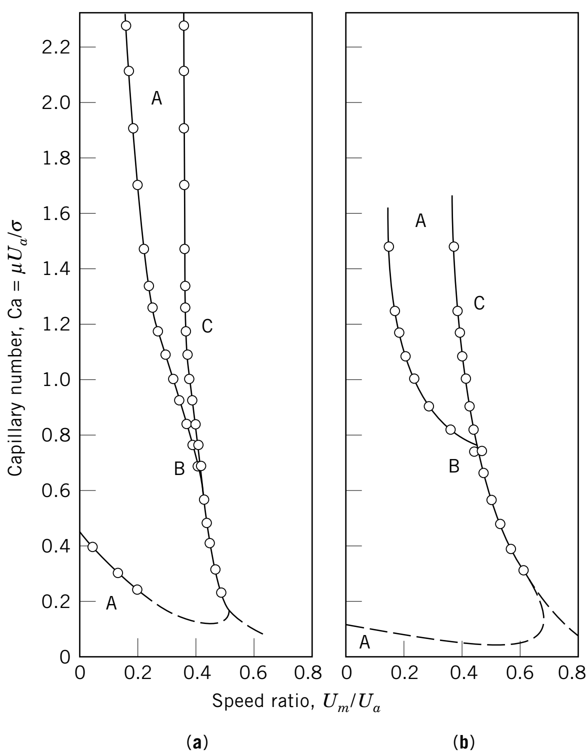

Fig. 12. Operability diagram for reverse-roll coating, where A represents a stable coatings area; B, ribbing; and C, cascade; for (**a**) a gap $G = 750$ μm and (**b**) a gap $G = 250$ μm (12).

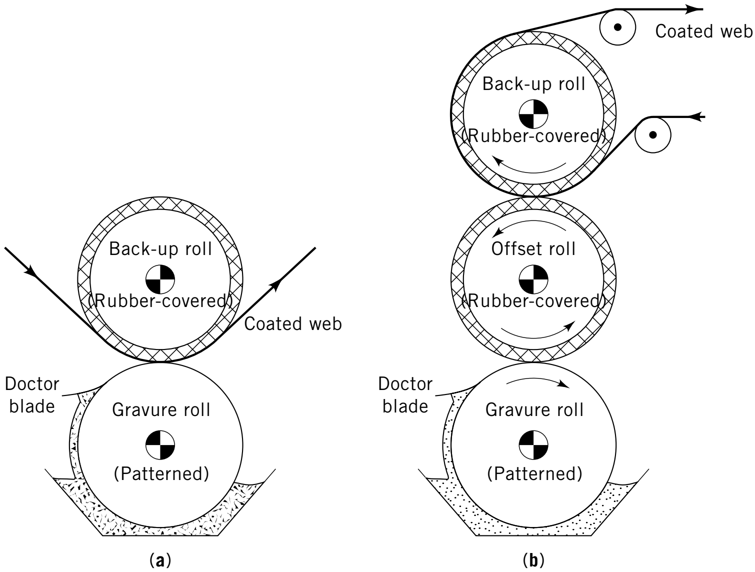

Fig. 13. Gravure coaters (**a**) direct; (**b**) offset (12).

Figure 13 illustrates two types of gravure coaters. In direct gravure the liquid is transferred directly from the gravure roll to the web. In offset gravure the liquid in the cells is first transferred to a rubber-covered offset roll before the final transfer to the web. In reverse gravure the gravure roll or the offset roll turns in the reverse direction with respect to the web. In differential gravure the forward rotating gravure cylinder runs at a different speed than the backing or impression roll. However, the web does not have to be held against a backing or impression roll; it can also be unsupported, as in kiss coating. The coating liquid can be applied to the gravure roll by a number of methods, not just by the pan-fed system illustrated.

The three common cell patterns for the gravure cylinder are illustrated in Figure 14. The pyramidal and quadrangular cells are similar, except that the quadrangular has a flat, not a pointed, bottom in order to empty easier. The trihelical pattern consists of continuous grooves spiraling around the roll, usually at a 45° angle. The volume factor is the total cell volume per unit area, and has units of height, typically ranging from 4 to 300 μm. The fraction of the cell volume that transfers varies greatly, depending on the system. With high impression roll pressures, about 58% of the cell volume normally transfers. The cell pitch or count is the number of cells per centimeter measured perpendicular to the pattern and usually ranges from 4 to 160 cm^{-1}. The pattern is made by mechanical engraving, chemical etching, electromechanical engraving, or laser etching.

After the gravure cylinder is coated with coating liquid, the excess is doctored off, normally using a 01- to 0.4-mm spring steel blade. Usually the doctor blade makes a $55-70^\circ$ angle with the incoming gravure roll surface and is oscillated 6–50 mm to give even wear and to dislodge dirt that could cause streaks. A reverse-angle doctor blade can also be used. It often makes an angle

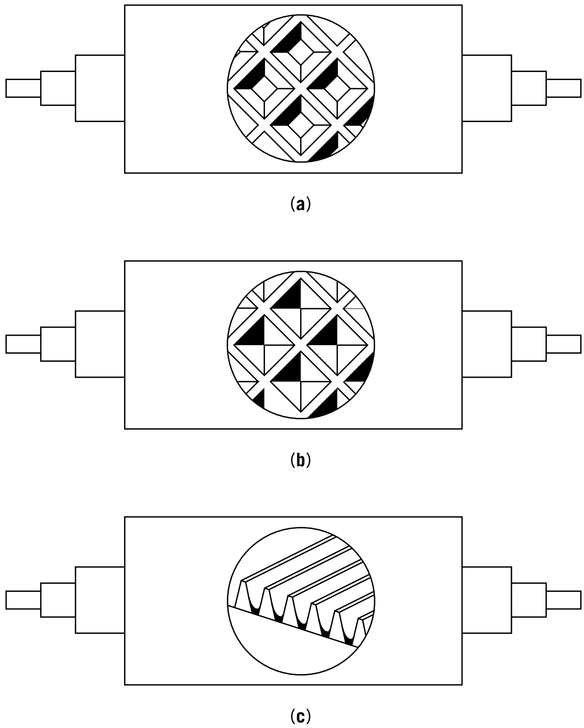

Fig. 14. Common cell patterns in gravure coating: (**a**) quadrangle; (**b**) pyramid; and (**c**) trihelical (2).

of 65–90° with the exiting surface. This blade does not have to be loaded against the cylinder face because fluid forces press the blade against the surface, and so the reverse blade can be made of softer materials, such as bronze or plastic. There is no need to oscillate this blade because in this position it cannot trap dirt; however, the standard blade is felt to do a better job of doctoring.

As with the flexible-blade coater, a softer doctor blade or one having a lower loading and an almost smooth cylinder with a shallow pattern allows excess liquid to pass through. A stiff, highly loaded blade against a cylinder having a large volume factor (cell volume per unit area) wipes the surface clean. The gravure roll has to be heavily loaded against the backup or impression roll in order to achieve good transfer to the web. The usual force is about 2000–20,000 N/m.

The most important factor in determining the transfer or web pickup is the gravure pattern design. The cell pitch controls the stability of web pickup. The leveling of the coating can be a problem. Large spacing between cells often results in printing of the cell pattern, rather than a uniform coating. Reverse and differential gravure tend to give better leveling. A smoothing bar can also be used.

A very useful new gravure coating technique is the Micro-gravure™ technique, which was introduced in the early 1990s. It is intended for low coating weight products on light gauge films for imaging, electronics, packaging, batteries, and other specialty applications. The unique features are the use of

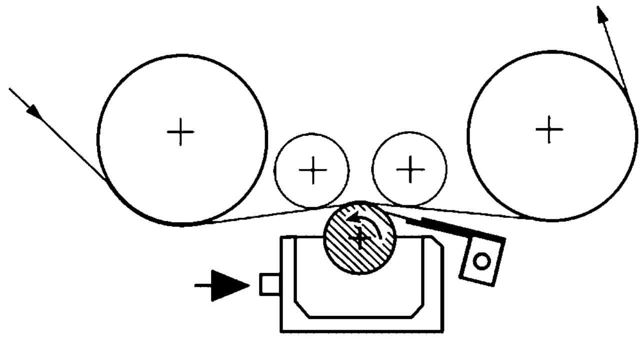

Fig. 15. Side view sketch of Micro-Gravure™ coating head. Courtesy of Yasui-Seikei.

small diameter rolls, 20–50 mm versus 150–300 mm for conventional gravure. This results in a small stable bead, which when combined with reverse application gives very good quality and a low coating weight. A typical configuration is shown in Figure 15.

3.6. Dip Coating. Dip coating is one of the oldest coating methods in use. Using continuous webs, the web passes under an applicator roll partially submerged in a pan of the coating fluid. The web is thus actually dipped into the coating solution. A doctor blade may be used to remove excess fluid if a reduction in the wet coating weight is desired. Otherwise the coverage is determined by coating speed and the characteristics of the liquid. The coverage increases with increasing viscosity and coating speed. Surface tension has a relatively small effect.

Dip coating is very commonly used for coating continuous objects that are not flat, such as fibers and for irregularly shaped discrete objects. Drops of coating at the bottom of dip-coated articles may be removed by applying electrostatic forces as the article is moved along a conveyor.

3.7. Extrusion. Extrusion coating and slot coating are in principle very similar. In extrusion coating a high viscosity material, often a polymer melt, is forced out of the slot of the coating die onto a substrate where it is cooled to form a solid coating. As can be seen in Figure 16**a**, the highly viscous liquid does not wet the lips of the die. Similarly in slot coating, a relatively low viscosity liquid, usually under several thousand mPa · s (=cP), often a polymer solution, is forced out of the slot and onto the web. In slot coating the coating liquid does wet the lips of the die, as shown in Figure 16**b**. Some engineers use the terms slot coating and extrusion coating interchangeably.

Extrusion coating is often used in food packaging where vapor and oxygen barriers are required and heat sealability is desired. The expanding food packaging industry is the direct result of packaging improvements that can be attained from improving the surface and physical characteristics of a flexible web by extrusion coating.

Because of the high viscosities involved in extrusion coating, the coating die and the auxiliary equipment are massive. An extruder is needed to heat and melt the thermoplastic polymer, the die is heated by electric heaters, and the die also

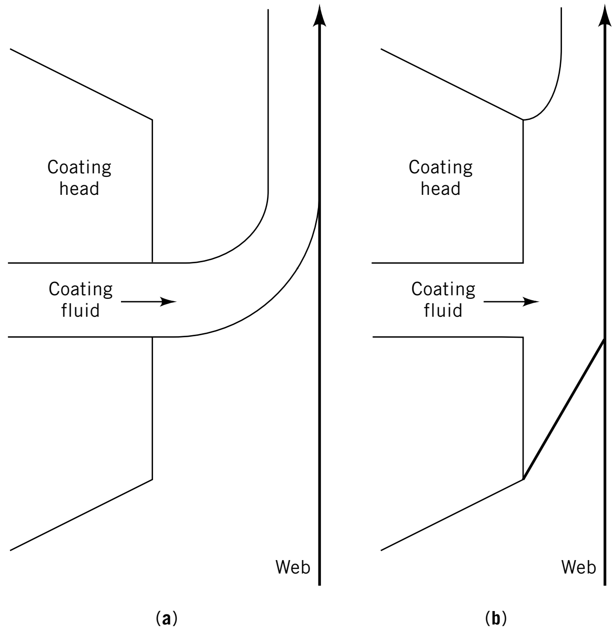

Fig. 16. Comparison of (**a**) extrusion coating and (**b**) slot coating.

contains adjusting bolts every 10 cm or so across the width that control the lip openings to try and obtain a uniform cross-web coverage. Internal choker bars controlled by bolts may also be used to adjust the uniformity. The bolts may be computer controlled. There may also be a laminating station to combine the plastic sheet with a substrate and to cool the laminate. The plastic may leave the die at about 175°C and may be about 0.5 mm thick. It is then elongated by the pulling effect of the faster-moving substrate which it joins in the pressure nip in the laminating section. The elongation reduces the width of the extruded film by perhaps 2–6 cm and reduces film thickness to approximately 12–25 μm before it makes contact with the substrate.

Good temperature control of the plastic and pressure control ahead of the coating die is important to the success of the coating. Variations in temperature lead to irregularities in the coating thickness both in the machine direction and across the web. Thickness variations in the cross-web direction can be reduced by adjusting the slot opening via the adjusting bolts and use of choker bars. The extruded film width is adjustable by external deckles to block off the exit of the die. In the laminator the nip helps to promote bonding, before chilling the molten plastic. The driven chill roll is chromium or nickel plated and can have a mirror, matte or an embossed surface. Once the extruded film passes through the laminating nip, it takes on the finish of the chill roll. The chill roll is 60–90 cm in diameter with perhaps a 120° wrap and utilizes refrigerated water to reduce the film temperature to about 65°C before the film is stripped. To improve adhesion of the extruded film to the substrate, adhesion-promoting “primers” are usually applied to the web before the laminator. Priming can be electrostatic (corona treatment), chemical, or in the form of ozone treatment. Coating weights are controlled by the line and extruder speeds, but in many cases the chill roll capacity limits the maximum thickness that can be obtained. Extrusion coating lines operate at speeds up to 1000 m/min and can apply 10–30 g/m^2 of coating.

3.8. Slot Coating. Slot coating (Fig. 16**b**) involves a relatively low viscosity fluid, under perhaps 10,000 mPa · s (=cP) and uses much simpler equipment than extrusion coating. An ordinary pump or a pressurized vessel feeds the fluid through a flow meter and control valve to the coating die, which often operates at room temperature. If heating is required, water flowing through internal channels is usually adequate. Because of the simple rheologies of the fluids, the die can be designed to give uniform flow across the width with no adjustments. In fact, an adjustable die should be avoided. It is not difficult to design the die to give uniform flow, but it is very difficult to make the exactly correct adjustments. Because the viscosity is relatively low the pressures within the die are also relatively low, and the die can be much less massive than an extrusion die and still withstand the spreading forces.

Normally the web is supported by the backing roll in slot coating. However, for very thin coatings, under about 15-μm wet, the gap between the coating lips and the web becomes very tight, under about 100 μm, and the system becomes difficult to control and operate. The runout of the bearings can become a significant fraction of the gap. Dirt can hang up in the gap to cause streaks. If the web contacts the coating die the web can tear, causing a shutdown of the operation. Coating against unsupported or tensioned web should be used for very thin coatings. In this case web tension becomes an important variable.

In slot coating, bead vacuum is often used to increase the window of coatability, that is to allow thinner coatings and perhaps to allow coatings at higher speeds. A vacuum box is placed under the coating die and a vacuum of up to about 1000 Pa (4 in. of water) is pulled by a vacuum fan. Higher vacuums may be needed for higher viscosity liquids. There should be a tight vacuum seal against the sides or ends of the rotating backing roll, but no rubbing contact where the web enters the vacuum chamber in order to prevent scratches. The air in the vacuum chamber can resonate as in a musical instrument. These pressure fluctuations can cause chatter at wide gaps. The air leakage should be kept as small as possible to reduce the amplitude of the pressure fluctuations.

3.9. Curtain Coating. Curtain coating is used to deliver coating liquid in a falling sheet or curtain to the substrate, which moves through the curtain at the coating speed. In one version a slot coating head is aimed downward and the coating emerges as a falling film or sheet as seen in Figure 17. The curtain thickness is controlled by the feed rate and by precise adjustments of the slot opening. The vertical distance of the coating die above the substrate can be adjusted. The falling curtain is protected from stray air movements by transparent enclosure sheets. Coating thicknesses as low as 12 μm are possible when coating with lacquers or with low viscosity wax melts, and are as low as 20 μm with hot-melt compositions of higher viscosity. There is no problem in obtaining heavier coating coverages.

Air-bubble entrapment may occur in the case of a gravity-applied continuous coating over an impermeable substrate. Bubbles may also be caused by moisture vaporization from the substrate. Remelting of the coating may minimize

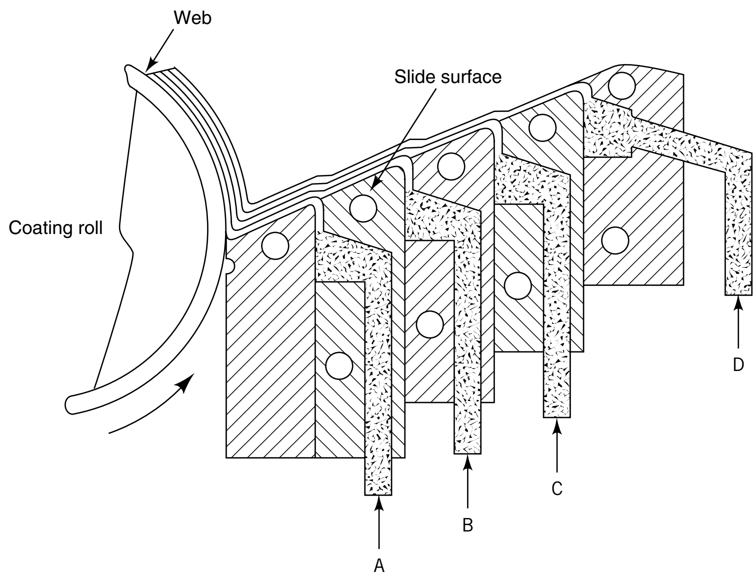

Fig. 17. A slide coater where A, B, C, and D correspond to the inlets for the liquids for layers 1, 2, 3, and the top layer, respectively (8,13).

the bubble defects. Curtain-coating equipment of this design is capable of operation at substrate speeds up to 500 m/min.

Curtain-coating equipment is also available in which the falling curtain is generated by overflow from an open weir. The coating is delivered to the open weir uniformly across its width by a pipe having diffuser jet openings. As the coating overflows the low side of the weir, it travels down a short flat skirt before dropping. The thickness of the falling curtain is adjusted by precise control of the rate of delivery of coating to the weir. Hot-melt coatings can also be applied by the open weir, as in the slot die. Because there is no close restriction to flow as in the slot die, the open weir does not tend to form scratches or coating streaks because of crusting or coating hang-up in the slot opening. When applying hot-melt coating formulations the coating supply is held in a reservoir at a temperature that does not thermally degrade the material during its residence. The coating is brought to this temperature using heat exchangers as it is pumped to the weir. Weir-type equipment is recommended for operation at substrate speeds up to 400 m/min. The coating fluid not carried away on the coated surface falls into a collection trough for recirculation.

Curtain coating is adaptable for coating irregularly sized sheets such as slotted cut-out corrugated carton blanks or sheets of plywood, as well as for continuous substrates. Coatings may also be applied to uneven geometric shapes such as blocks. The principal limitation of curtain coating is that a high flow rate of about 0.5–1.5 $cm^3/(s{\cdot}cm$ width) is needed to maintain an intact curtain. Usually about double this minimum is desirable. Thus, to obtain a thin coating, high coating speeds are required. Curtain coating is inherently a high speed process and the curtain will not form at low speeds or flow rates.

4. Multilayer Methods

4.1. Slide Coating. Slide coating is the primary method for simultaneously coating a multilayer structure. A slide coater, illustrated in Figure 17, can coat an unlimited number of top layers, 18 or more, simultaneously. Each layer flows out onto the slide yet does not mix with the other layers as they all flow together down the slide, across the gap, and onto the web, all in laminar motion. Slide coating is extensively used in coating photographic films and papers, both color and black and white. In color films, nine or more layers are coated simultaneously.

Instabilities can form on the slide in the form of interfacial waves, which may disturb the desired laminar flow and cause mixing. The closer the physical properties of all the layers are, the closer the system resembles a single layer in which internal waves do not form. The densities of the individual layers are always reasonably close to each other, and are usually not subject to control. The viscosities of adjacent layers should generally not vary by too much (14). It has been suggested that to avoid these waves the ratio of the viscosity of a layer to that of the adjacent lower layer should be more than 0.7 and less than 1.5 or 2 (15). However, if the ratio is above 10, waves again do not form. The bottom layer should have the lowest viscosity to reduce drag forces and allow higher coating speeds.

As with slot coating, a slight vacuum (up to 1 kPa for the usual low viscosity fluids) under the coating bead aids in coating by allowing thinner coatings and higher coating speeds. The bottom edge of the slide should be sharp and have a small radius of curvature, no more than about 50 μm or so, to pin the bottom meniscus and reduce the chance of cross-web barring or chatter.

4.2. Precision Multilayer Curtain. A variation of curtain coating can also be used to produce multilayer coatings. A slide is used to generate the multilayer structure which then flows over an added lip of the die to form a curtain. Edge guides are used to prevent the curtain from necking in because of surface tension. For precision coating the curtain has to be completely uniform across the width. Precision multilayer curtain coating is used to coat color photographic materials. This is illustrated in Figure 18. In most precision coatings the curtain is narrower than the web.

4.3. Slot Coating. Multiple layers can be coated simultaneously from a slot-coating die with multiple slots. The layers come together in the coating bead to form the final coating. Multiple layers in slot coating work well, but the die internals are complicated, especially when more than two layers are involved. This technique is particularly useful for coating of organic solvent systems, since the enclosed bead minimizes evaporation.

4.4. Extrusion Coating. In the most popular method of multilayer extrusion coating, the several layers come together before the coating die in a combining adapter or block, and then exit as one stream into the extrusion die (see Extrusion). The extrusion die is a standard single layer die, except that the feed port is rectangular to match the dimensions of the rectangular sandwich formed in the combining adapter. The separate layers remain distinct in the combining adapter and in the die. As long as the viscosity ratios are no greater than about 3:1 under processing conditions, the layer uniformity should be acceptable.

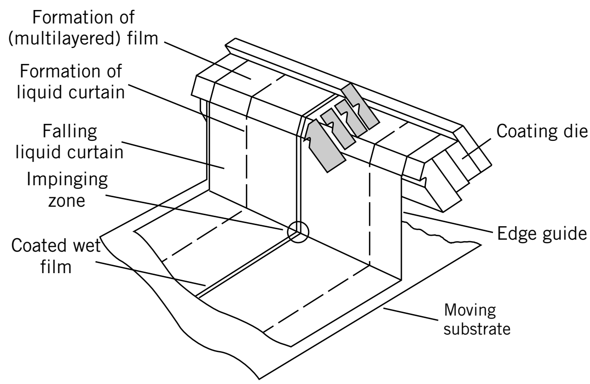

Fig. 18. Curtain-coating apparatus (13).

Multilayer extrusion provides the unique capability of producing layers of different resins to give superior functional properties. For example, an inexpensive resin can be used as the core of a three-ply extrudate, the outer plies being more expensive but also much thinner than if extruded alone.

5. Discrete Surface-Coating Methods

A variety of coating techniques are available to coat surfaces which are planar and have irregular surfaces.

5.1. Spray Coating. Coatings may be applied by spraying the coating material onto the object to be coated, which may be irregularly shaped with compound curves and with sharp edges. Many coating powders of suitable dielectric constant may be electrically polarized so that the powders are attracted to a grounded or oppositely charged surface. The object may then be heated to fuse the powders into a continuous film.

5.2. Dip Coating. The dip-coating technique described for webs can also be used to coat discrete surfaces such as toys and automotive parts. The item to be coated is suspended from a conveyor and dipped into the coating solution. The item is then removed; the coating drains and then levels to give the desired coverage. The object is then dried or cured in an oven.

5.3. Spin Coating. Spin coating is used to produce a thin uniform coating on discrete supports. In this process the coating fluid, usually a colloidal suspension, is placed on a horizontal substrate which rests on a rotating platform. The speed of the platform is increased to the desired level, which can be as high as 10,000 rpm. Centrifugal forces drive much of the coating off the support, leaving a thin, uniform film behind. In addition, the coating is drying during the process and as a result the viscosity increases, resistance to flow occurs, and a level thin coating is left. The coating chamber can provide hot air to the coating to dry or cure the remaining film. Additional coatings of different coating materials can be applied to develop a multilayer structure. This process is used to coat structures such as photomasks, magnetic disks, optical coatings, and a variety of layered products in the microelectronics industry.

5.4. Vacuum Deposition Techniques. Thin coatings are applied to a variety of substrates for use on semiconductors, ceramics, and electrooptical devices, using a wide variety of vacuum deposition techniques. Vacuum deposition is a rapidly advancing area of coating technology. In these processes the support to be coated is placed in a vacuum chamber which contains the coating material. Typically the coating material is a metal such as aluminum, gold, or tungsten. A high vacuum is then pulled; electrical energy or an electron beam is applied to heat the metal which evaporates off to deposit on the substrate. In sputtering, an ion beam is used to knock off atoms of the metal at lower temperatures. Individual supports, such as a target to be examined in a scanning electron microscope, or a continuous web, such as in making metallized poly-(ethylene terephthalate), can be used. The coatings can be continuous, or patterns or electrical circuits can be made if the support is masked.

There are several vacuum processes such as physical vapor deposition, chemical vapor deposition, sputtering, and anodic vacuum arc deposition. Materials other than metals, such as tetraethylorthosilicate, silane, and titanium aluminum nitride, can also be applied.

6. Patch Coating

It is sometimes necessary to coat patches of material on a web, such as coating the anode and cathode in batteries and in fuel cell membranes (Fig. 19). With these products an uncoated border is required around the coating to prevent a short circuit. Gravure coating is well suited for this purpose because the desired pattern can be etched into the gravure cylinder. Slot-coating techniques are also used (16). With slot coating there is the problem, however, of nonuniform coverage at the start and end of the patch, and the thicker edges along the sides. The start and end problems may be minimized by carefully controlling the flow with pumps and valves.

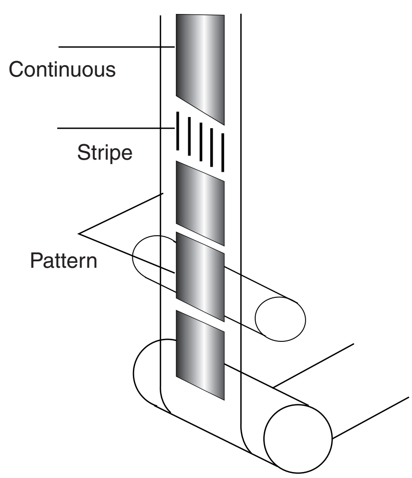

Fig. 19. Patch coating.

7. Coating Process Mechanisms

One of the principal advances in the coating process area in the 1980–1990s was the development of techniques to understand and define basic coatings mechanisms. This has led to improved quality and a wider range of utility for most coating techniques. This has involved the computer modeling of the coating process and the development of visualization techniques to actually see the flows in the coating process. The flow patterns predicted by the computer models can be verified by the visualization techniques.

Free surfaces and interfaces make the physics of coating flow systems extremely difficult to model by classical mathematical methods. As a result, coater designs and parameter ranges for defect-free coating have traditionally been determined through expensive and time-consuming statistical experimentation. Therefore coating developed largely as an art rather than a science. The ability to model the coating process by using modern methods of numerical and functional analysis, and to explain many of the complex mechanisms of coating instabilities and the resulting defects, is thus refreshing.

The most successful models are based on the finite element method. The flow is discretized into small subregions (elements) and mass and force balances are applied at each node. The result is a large system of equations, the solution of which usually gives the velocity and pressure of the coating liquid in each element and the location of the unknown free surfaces. The smaller the elements, the more the equations, which are often in the range from 10,000 to upwards of 100,000.

It is now possible to simulate steady transversely uniform flows of Newtonian or non-Newtonian liquids by using commercially available software packages such as FIDAP, NEKTON, FLUENT, PHOENICS, and POLYFLOW. Using these codes it is possible to locate regions of flow recirculation that may cause coating defects as a result of the increased residence time of solution. The free-surface handling capabilities of currently available commercial codes are limited to relatively simple steady flows and the transient response to specified transversely uniform disturbances. For a steady uniform flow to exist in nature, however, it should be able to recover from all small disturbances, such as building vibrations and the molecular fluctuations that are always present. Flow instabilities resulting in defects such as ribbing cannot be predicted by commercial software. Using more advanced methods developed first at the University of Minnesota and now in widespread use (17–20), it is now possible to predict most coating flow instabilities including bead break-up, flooding, cross-web barring (chatter), down-web ribbing, and diagonal chatter. It is also possible to follow the longtime development of the resulting defects and to explore parameter ranges of stable, defect-free operation (coating windows) at a fraction of the cost of the actual physical experiments. In a computer model the geometry can be quickly changed without having to construct expensive new parts. Considerable time and cost savings can be realized by optimizing coating systems computationally.

Experimental techniques to visualize flows have been extensively used to define fluid flow in pipes and air flow over lift and control surface of airplanes. More recently this technology has been applied to the coating process and it is now possible to visualize the flow streamlines (15,21). The dimensions of the flow field are small, and the flow patterns both along the flow and inside the flow are important. Specialized techniques involve generating small hydrogen bubbles using fine electrodes and injecting dyes in the regions of interest; optical sectioning is then required to observe and to photograph these flows.

A stereo zoom microscope having a very small depth of field and a clear window on the side of the applicator is employed. Fiber optic cables may be used for remote viewing. Accurate control of the light level and position is needed to reduce reflections that may mask the details of the flow field. The microscope is focused at varying points and flow nonuniformities are recorded. Using this technique, air entrainment, flow recirculation in the bead, curtain-coating formation, and the teapot effect have all been visualized for many types of slot, slide, and curtain coatings. This information leads to an improved understanding of the coating process. The same technology can also be applied to many other types of coating.

8. Drying and Solidification

The coating solution after application is in the liquid state and must be solidified. For coating with solvents, including water, this is brought about by removing the solvent, ie, drying. The drying process after the application of the coating is as important as the coating process itself. The properties of the coating are not complete until solidification has occurred. The coated film or web is transported through the dryer where the properties of the coating can either be enhanced or deteriorated by the drying process. Drying of coatings involves the removal of the inert inactive solvent used to suspend, dissolve, or disperse the active ingredients of the coating, which include polymeric binder, pigments, dyes, slip agents, hardener, coating aids, etc. Coating solvents range from the easy-to-handle water to flammable and toxic organic materials. Drying must occur without adversely affecting the coating formulation while maintaining the desired physical uniformity of the coating.

For polymer melts and for certain materials that gel on cooling, such as gelatin solutions, the temperature is lowered to solidify the coatings. With gelatin gels drying is still necessary. Similar hardware can be used for both heating and evaporation and for cooling, since they are both heat transfer devices.

While drying is a physical process involving only solvent removal, solidification can occur by cross-linking liquid monomer or liquid low molecular weight polymer. This can be accelerated by catalysts or can be accomplished by an electron-beam or uv radiation. This cross-linking process is called *curing*. Material coated from solution often also undergoes curing to improve the physical properties of the dried coating. Thus both curing and drying may occur in the dryer. This takes place with aqueous gelatin coatings which are cured using aldehyde cross-linkers. The cross-linking starts in the dryer.

The dryer provides heat to volatilize the solvent and a means to carry the solvent away from the coating. Efficient hardware is used to minimize energy costs. The dryers may be equipped with the appropriate pollution abatement devices to meet both OSHA and EPA standards. Dryers commonly use hot air both to provide heat and to carry away the solvent. The air may be heated by steam or by heat exchange with flue gases. Flue gases from the combustion of natural gas may be used directly in place of hot air. Infrared radiant energy from gas combustion or electric resistance heaters is sometimes used. Conduction heat transfer from heated drums is also used. The choice depends on availability of supply, the temperature range desired, and costs. Dryers can also use other sources of energy such as microwaves or radio-frequency waves. However, air is still needed to carry off the evaporating solvent. Radiant energy tends to be more expensive and is only used in special circumstances. If the coating can react with oxygen or if the solvents are flammable, inert gases such as nitrogen may be used in place of the air.

Because the evaporation of the solvent is an endothermic process, heat must be supplied to the system through conduction, convection, radiation, or a combination of these methods. The total energy flux into a unit area of coating, q_{t}, is the sum of the fluxes resulting from conduction, convection, and radiation.

Although heat transfer by conduction from heated drums is used extensively in the paper industry, convective heat transfer is very popular and used in most coating operations. Here the main focus is on convective heat transfer.

The rate of convective heating can be estimated as

$$q_{\mathrm{convection}} = hA\Delta t$$

where A is the area (m^2), h is the heat-transfer coefficient [$\mathrm{W/(m^2 \cdot K)}$], q is the rate of heat transfer (W), and Δt is the temperature difference between the hot gas and the coating (K).

The heat-transfer coefficient is a key property of the dryer. It is controlled by the nozzle geometry and spacing, the distance from the web, and the velocity of the air. The evaporation rate is the rate at which heat is supplied for evaporation (heat also goes into heating the coating and the web) divided by the latent heat of vaporization of the solvent.

8.1. Air Impingement Dryers. Air impingement dryers, the most widely used for drying coated webs, basically consist of a heat source and heat exchangers (unless hot flue gas from combustion of natural gas is used), fans to move the air, ducts and nozzles or air delivery devices positioned close to the web, and solvent removal ducts. If all the air is recirculated, then equipment to remove solvent from the air is also provided. Figure 20 shows a typical dryer. In addition, there are controls for the air temperature and the air velocity from the nozzles and, in some cases, for the solvent level in the drying air. There may also be controls to keep the solvent concentration well below the lower explosive unit. Dryers often have separate sections or zones where the air temperature and velocity (and perhaps solvent level) can be controlled independently.

The dryer must also transport the web through the dryer using a combination of driven and idler rolls. The web path can be either horizontal or vertical, or, with the appropriate web-turning devices, fold back upon itself to conserve space. The idler rolls in single-sided dryers should be spaced so that there is enough wrap for the web to turn the rolls, and the coating should be kept within the effective area of the nozzles. Sometimes the web slips on the idler rolls and gets scratched. To prevent this the idler rolls can be driven by tendency drives

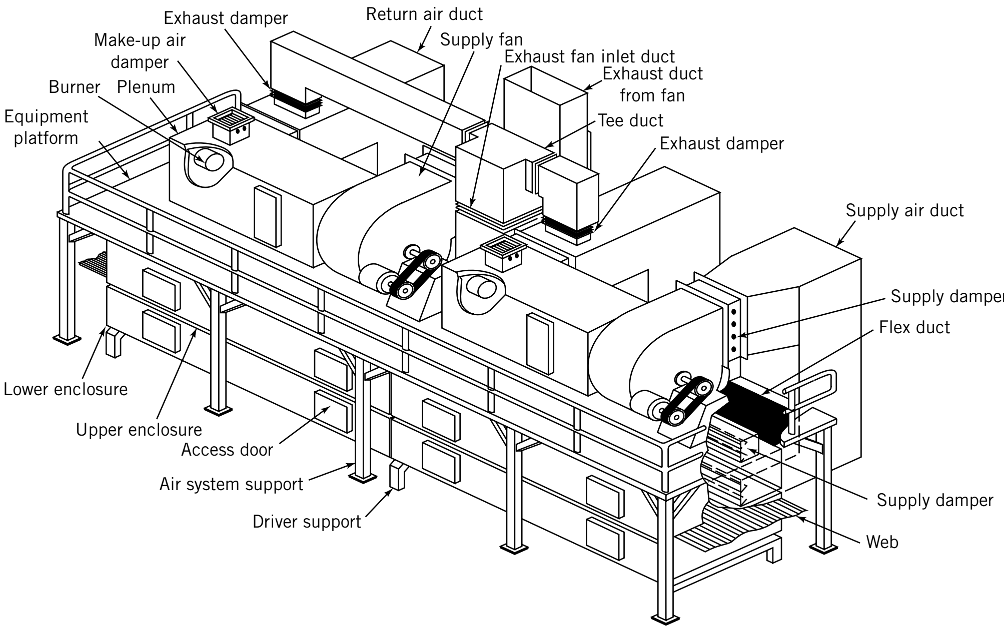

Fig. 20. Dryer components of a top mounted air system dryer. Courtesy of MEGTEC Systems.

which have two sets of bearings. The axle is driven at approximately the speed of the web, and the roll idles at this speed on a separate set of bearings. The driven web then easily brings the roll to the exact speed of the web. Tendency drives are needed for light webs. Typically the web should be within six to seven nozzle slot widths of the impingement nozzles.

In these single-sided dryers, the air impinges only on the coated side, heating and drying from that side only. The air can be delivered to the web from plenums with slots, with holes, or from specially designed nozzles. In a basic configuration the nozzles and idler rolls are contained in insulated boxes to minimize heat losses, solvent escape, and noise. The efficiency of the dryers depends on the heat transfer coefficient, the air usage, the temperatures used, and the solvent level. Wet coatings flow easily and the drying air should not disturb them.

The two-sided or floater dryer is now most often used. In this configuration the roll transport system in the dryer is replaced with air nozzles on the back side of the web so that the air transports and supports the web as well as heating and drying it from both sides. When impervious webs are used, while the heating is from both sides, the drying is only from the coated side. The two-sided heat transfer results in higher drying rates and thus shorter dryers, while eliminating problems of scratching from the idler rolls. However, more air is used.

Two types of floater nozzles are currently in use. One, based on the Bernoulli principle, is used in the airfoil flotation nozzles in which the air flows from the nozzle parallel to the web and the high velocities create a reduced pressure, which attracts the web while keeping it from touching the nozzles. The

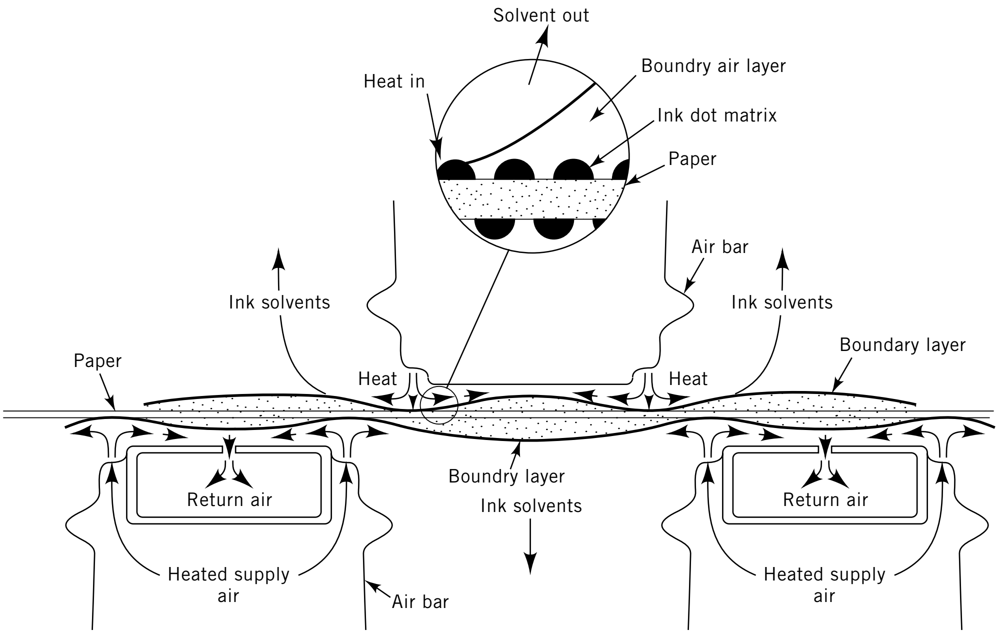

Fig. 21. Coanda effect air bars. Courtesy of MEGTEC Systems.

other uses the Coanda effect to create a flotation nozzle where the air is focused and follows the contours of surface of the air bar chamber, thus creating a pressure pad which supports the web, as shown in Figure 21.

Air flotation dryers have excellent heat-transfer coefficients, give very uniform drying across the web, and give excellent web stability. They can be used for a wide range of web types and tensions, and tend to be quieter, and thus pose less noise problems than the higher velocity single-sided dryers. Floater dryers are totally enclosed and compact so that they are clean and cause less dirt defects in the coating.

Single-sided dryer air velocities are 150–600 m/s, giving heat-transfer coefficients of 30–140 W/($m^2 \cdot$ K). Floater dryers operate at slightly lower (150–500 m/s) slot velocities, and have higher [50–275 W/($m^2 \cdot$K)] heat-transfer coefficients based on the same single-sided web area.

8.2. Contact or Conduction Dryers. Coatings on webs, as well as sheets of newly formed paper, can be dried by direct contact with the surface of a hot drum. The drum is usually heated by steam. Here conduction is used to transfer the heat. Air still has to be supplied to carry away the solvent vapors. Drums can also be used to rapidly cool warm extruded films, to increase the viscosity, and to solidify the film.

8.3. Radiation Drying. Infrared or microwave radiation can supply concentrated energy to the web to evaporate the solvent, but air must still be used to carry away the solvent. These techniques provide a high heat input over short distances. Often Infrared is used in conjunction with convection dryers. It is often used at the start of drying to rapidly solidfy the coating, with the balance of drying done in convection oven. This can be cost efficient. Infrared heaters can be placed between the air nozzles. This increases the drying rate and thus the production rate without increasing the length of the dryer, and without requiring additional air handling systems. Use of Infrared heating is most effective in the first sections of the dryer, in the constant rate period, where the coating is coolest and most of the added heat, including that by Infrared radiation, goes to evaporate the solvent. In the falling rate period in most cases the drying rate is the rate of diffusion of the solvent to the surface, which is influenced only by the temperature. Infrared heating can only raise the temperature faster, which usually has just a minor effect.

8.4. Pollution Control. The solvent removed during drying is frequently a pollutant and the exhaust air must be treated to ensure that it meets government standards before being discharged to the atmosphere. The two basic approaches to treating the air are to recover the solvent for reuse and to convert it by burning to compounds which can safely be discharged. The basic solvent recovery systems involve condensation or adsorption in a charcoal bed. After recovery the solvent needs to be purified before reuse. For combustion of the exhaust sovent both thermal and catalytic systems are used. Pollution control systems are an essential part of the drying process and are available from dryer manufacturers. One should reduce the amount of volatile solvents in the coating process by coating as concentrated a coating fluid as possible. One should also investigate changing to a water-based system.

8.5. Modeling Convection Drying. Models of the drying process have been developed to estimate whether a particular coating can dry under the conditions of an available dryer. These models can be run on personal computers.

To model convection drying in the constant rate period both the heat transfer to the coated web and the mass transfer from the coating must be considered. The heat-transfer coefficient can be taken as proportional to the 0.78 power of the air velocity or to the 0.39 power of the pressure difference between the air in the plenum and the ambient pressure at the coating. The improvement in heat-transfer coefficients in dryers since the 1900s is shown in Figure 22. The mass-transfer coefficient for solvent to the air stream is related to the heat-transfer coefficient by the Chilton–Colburn analogy (23,24):

$$\frac{h}{\rho c_{\mathrm{p}} k_{\mathrm{m}}} = N_{\mathrm{Le}}^{2/33}$$

where c_{p} is the heat capacity of the air $[\mathrm{J/(kg \cdot K)}]$, h is the heat transfer-coefficient $[\mathrm{W/(m^2 \cdot K)}]$, k_{m} is the mass-transfer coefficient $\{\mathrm{kg/[s \cdot m^2 \cdot (kg/m^3)]}\}$, N_{Le} is the Lewis number, equal to the thermal diffusivity of the air divided by the mass diffusivity of solvent vapors in the air, and ρ is the density of the air $(\mathrm{kg/m^3})$.

The total heat transfer to the coated web is then equated to the heat consumed by the evaporating solvent and the heat used in heating the web and the coating. This allows calculation of the temperature of the coated web (14,25). For single-sided drying, the equilibrium constant rate web temperature is the wet-bulb temperature of the air for that particular solvent. In the constant rate period of drying the coating behaves as if it were a pool of solvent. When dry patches appear on the surface, the rate of drying decreases and the falling rate period begins.

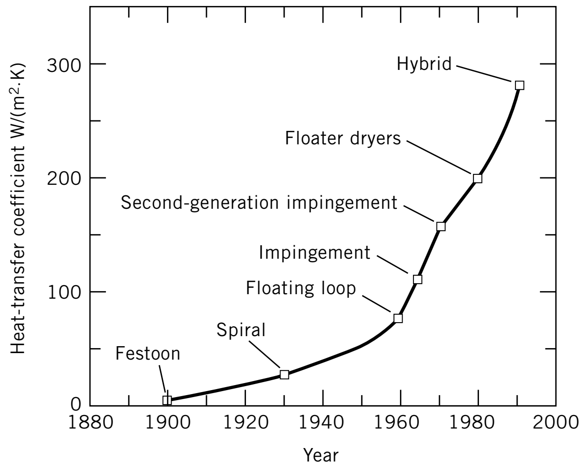

Fig. 22. Improvement in dryer heat-transfer coefficients over time (22). To convert $W/(m^2 \cdot K)$ to $Btu/(h \cdot ft^2 \cdot °F)$, multiply by 0.176.

Modeling the falling rate period is more difficult, because the drying rate then depends on the mechanisms occurring within the coating. In coating on impervious webs the rate-limiting process is diffusion; in porous coatings and coatings on porous paper it may be capillary action. In aqueous coatings most of the drying occurs in the constant rate period; for organic solvent systems most of the drying occurs in the falling rate period, to the extent that in some cases the constant rate period is over before the coated web enters the dryer. In the falling rate period all the solvent that reaches the surface evaporates; thus the rate of diffusion to the surface is the rate of evaporation (if diffusion is the transport mechanism).

The higher the air temperature, the more rapid the drying. However, there are temperature limitations both for the web and for the coating. Plastic films should not be heated above their glass-transition temperature (the softening point) to prevent distortion and stretching. The coatings themselves may have a maximum temperature above which the coating may degrade. Many photographic coatings, for example, should not be heated above about 50°C.

8.6. Rheology. Rheology is the science of deformation and flow of matter. Because the coating process creates shear and extensional stresses in the coating fluid, the rheological properties of coating liquids are important factors in the selection and successful running of a coating operation. The coating hardware exposes the coating solution to a wide range of shear rates (Table 2). As a first approximation, the extensional rates would be of the same order as the shear rates. Shear and extension affect the properties of the solution. Therefore, the rheological properties, the deformation and flow under stress, are important factors in the selection and successful running of a coating operation.

The shear or dynamic viscosity is the ratio of shear stress to shear rate, and measures the resistance of the fluid to flow while undergoing shear. The common unit of viscosity is centipoise (cP). One cP is the same as 1 mPa·s. A high viscosity

Table 2. **Coating Process Shear Rates**

	Shear rate, s^{-1}
Coating	
dip	10–100
roll, reverse	1,000–100,000
roll, forward	10–1,000
spray	1,000–10,000
slide	3,000–120,000
gravure, reverse	40,000–1,000,000
gravure, forward	10–1,000
slot die	3,000–100,000
curtain	10,000–1,000,000
blade	20–40,000
Ancillary operations	
simple mixing	0–100
high shear mixing	1,000–100.000
Measurement	
Brookfield	1–100
Haake	1–20,000
Cannon-Fenske glass	1–100

solution flows slowly. The shear rate is the rate of change of velocity with distance in the direction perpendicular to flow and can be crudely approximated by the coating speed divided by a coating gap. In coating flows it can reach values over 10^5 s^{-1}. In simple or Newtonian fluids the viscosity is a constant and does not change with shear rate. However, it is not constant in dilute polymer solutions, where the shape of the polymer molecules distort with shear. The spherical shape of a random coil becomes elongated in the direction of flow and so offers less resistance to flow. Thus the viscosity decreases with shear rate. At very low shear rates, such that the shape of the molecules has not yet changed, the viscosity is constant at its zero shear value. At high shear rates where the molecules are fully elongated, such that they cannot offer less resistance with increasing shear, the viscosity is again constant, now at its infinite shear value (assuming the molecule is not destroyed by the mechanical forces). Almost all coating fluids contain dissolved polymers and are shear thinning.

Extensional or stretching flows are also very important in coating. The extensional viscosity is the ratio to the tensile stress in the fluid to the extension rate. Fluids can support a tensile stress when they are in motion. If you put a finger in a jar of honey and withdraw it, a strand of honey will be carried along by the finger. If you stop moving the finger the honey will fall back in the jar. But while in motion the honey will be in tension. With Newtonian fluids the extensional viscosity is three times the shear viscosity. When polymer solutions are stretched slowly, the molecules can relax, disentangle, and slip past each other. At higher extension rates they do not have time to relax and disentangle, and the extensional viscosity increases. This aids the coating process, and polymer solutions are easier to coat than Newtonian fluids of the same low shear viscosity.

The extensional thickening of polymer solutions is one form of viscoelastic behavior. This ability to support a tensile stress can also be demonstrated in a tubeless syphon with dilute aqueous solutions of polymers such as polyacrylamide or polyethylene oxide. If you suck up solution with a medicine dropper attached to a water aspirator and then lift the dropper out of the solution, the solution will still be sucked up. In shear, viscoelastic fluids develop normal stresses, which causes rod climbing on a rotating shaft, as opposed to the vortex and depressed surfaces that form with Newtonian liquids. Polymer solutions and semiliquid polymers exhibit other viscoelastic behaviors, where, on short time scales, they behave as elastic solids. “Silly putty,” a childrens toy, can be formed into a ball and will slowly turn into a puddle if left on a flat surface. But if dropped to the floor it bounces.

Concentrated dispersions may be shear thickening, as opposed to the shear thinning of dilute polymer solutions. Some materials, such as latex paints, tend to form a structure. As the structure breaks down with shearing action, the viscosity decreases. Such materials are thixotropic. Some fluids have a yield stress. A thorough characterization of the rheology may require a number of different measurements.

8.7. Surface Forces. Because fresh surface is created during coating, surface forces are involved. These are normally expressed as surface tension, in dyn/cm, which is identical to mN/m. Surface tension is identical to surface energy, expressed as erg/cm^2 or mJ/m^2. Whether we call it surface tension or surface energy is a matter of personal preference. Surface tension gives rise to a higher pressure on the concave side of a curved interface; thus the pressure on the inside of a drop is higher than on the outside. This higher pressure is called capillary pressure. It can be used to explain the shape of some coating beads.

In coating, the coating fluid should spread out on the support. For this to occur the surface tension of the fluid should be low and the surface energy of the support should be high. The contact angle in a drop of fluid on the surface, between the surface of the support and the surface of the fluid measured through the fluid, is a measure of the ability of the fluid to wet the surface. This contact angle should be low.

The surface energy of the support may be increased by oxidizing it, such as in a flame (flame treatment) or in an electrical discharge (corona treatment). Flame treatment is permanent, but for many polymers corona treatment is labile—after a matter of hours or days the surface energy decreases toward its original value. Because of this, corona treatment is done in-line, before the coating stand. High energy coatings may be applied to the support, such as the subbing often used on supports for photographic coatings.

The surface tension of a fluid containing surfactants varies with the age of the surface. As surfactant diffuses to the surface it lowers the surface tension; fresh surfaces have the higher surface tension of the solvent. The time for the surface to reach equilibrium varies from a number of milliseconds to several hours, depending on the system. The surface tension as a function of time is called the dynamic surface tension.

Similarly, the contact angle of a fluid on a support depends on whether the fluid is stationary or is moving, and at what speed. The contact angle for a stationary drop is lowest; as one coats faster in a coating operation the dynamic contact angle increases. When the coating speed increases to the point where the dynamic contact angle is 180°, air will be entrained and one can no longer coat.

8.8. Commercial Availability. All of the many types of coaters and dryers discussed herein are commercially available from many different vendors. These vendors usually have pilot facilities so that new coating and drying techniques can be easily tested. Contract coating companies, specializing only in coating, also exist.

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